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SOLID-STATE TECHNIQUES FOR MODULATION AND DEMODULATION OF OPTICAL WAVES

Report No. 2
Contract No. DA 36-039-SC-89221
(Second Quarterly Report)

DA Project No. 3A-99-21-001

Second Quarterly Progress Report
1 August 1962 Through 31 October 1962

US Army Electronics Research and Development Laboratory
Fort Monmouth, New Jersey

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OF OPTICAL WAVES

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1 Aug[redacted]-31 Oct[redacted]62

Methods are being investigated for modulation
and demodulation of light waves.

Prepared by
8 Dayton D. Eden
Member of Technical Staff
Texas Instruments Incorporated

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(9) 17 January 1963

SOLID-STATE TECHNIQUES FOR MODULATION AND DEMODULATION OF OPTICAL WAVES

(11) Texas Instruments ~~Report~~ No. U2-74000-2

SECTION I

PURPOSE

A theoretical and experimental study is being conducted for the purpose of examining methods of modulating and demodulating light beams for transmission of high-volume information.

The program has until now been restricted to solid-state effects.

Tasks under this program may be defined as achieving the desired (1) modulation and (2) demodulation.

Phases of the work have been delineated approximately as follows:

Toward solution of the modulation problem:

(Pockels) Several modulator geometries for use with KDP, ADP, cuprous halides and quartz have been investigated.

(Non-Pockels) Measurements program is being set up as a means of investigating semiconducting and ferroelectric materials.

For achieving adequate demodulation:

A number of silicon and germanium junctions have been fabricated and are presently being evaluated.

Evaluation facilities have been constructed to establish optimum configurations and materials.

A resonant microwave receiver has been constructed to match the photodiode outputs to a load from which the signal can be extracted.

SECTION II

ABSTRACT

A number of wide-band modulators (dc to 500 mc and higher) have been constructed using KDP. Y-cut quartz is being designed into a TEM travelling wave structure.

Pure cuprous chloride crystals are being grown for specific application in wideband TEM phase modulators.

An optical FM to AM converter using rutile is being prepared.

Good audio reception has been obtained at 1000 feet using gallium arsenide light-emitting diodes and silicon detectors in hand-held units.

A number of pill package photovoltaic detectors have been fabricated; typical junction capacitances are on the order of 1 picofarad and typical base resistances are approximately equal to 2 or 3 ohms. A smaller junction diameter of 4 mils appears possible by using new masking and etching techniques.

Modulated light from a gallium arsenide diode has been detected (using an air path) by a germanium photodiode at approximately 100 mcps.

Modulated light from a gallium arsenide diode at 900 mcps was detected by a silicon photovoltaic detector, using, for a light path, a tapered glass rod bonded to both source and receiver.

SECTION III

PUBLICATIONS, LECTURES, REPORTS, CONFERENCES

There have been no publications, lectures, or reports during this reporting period.

Dr. D. D. Eden visited the US Army Electronics Research and Development Laboratory at Fort Monmouth, New Jersey, on 31 August 1962 to deliver the preliminary draft of the First Quarterly Report and discussed its contents with the contracting officer's technical representative, Mr. Herbert Mette.

SECTION IV

FACTUAL DATA

A. MODULATION

1. Pockels Modulation

As has been previously mentioned in the First Quarterly Progress Report[1], the optical modulation effort at Texas Instruments emphasizes the utilization of the electro-optic or Pockels effect in certain crystalline solids. A materials measurements program also exists. Its objective is to establish the suitability of new electro-optic and other types of materials.

As was also pointed out in the First Quarterly Progress Report, light modulation, by means of the Pockels effect, is achieved by taking advantage of the fact that the electric field-induced birefringence may be converted to amplitude modulation by suitably chosen and oriented, polarizers and analyzers. By linearly polarizing the incident light in a direction which coincides with one of the crystal axes of the electro-optic material, phase modulation is obtained without the aid of an analyzer.

If the phase modulation is rapid (i.e., the modulation frequency is high) significant frequency modulation is effected with a theoretically very high deviation ratio.

The materials most thoroughly investigated to date have been ADP and KDP. Initial successes in achieving quite wideband modulation with these crystals have not been significantly improved upon during this report period. It appears that, without going to considerable design effort, dc to approximately 500 mcps is about the practical limit. It is true that much higher modulation is achievable but only if the modulation bandwidth is very small. For example, an X-band pulsed KDP modulator has already been discussed in the First Quarterly Progress Report, but with a bandwidth of only a few mcps. Various descriptions of microwave modulators using KDP have been reported in the literature,[2,3] but, as far as is known, their

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[1] First Quarterly Report, Contract No. DA 36-039-SC-89221, Report No. U1-74000-1, Texas Instruments, Dallas, Texas (Oct. 1962).

[2] Billings, B.H., Journal of The Optical Society of America, Vol. 39, No. 10 (1949), pp. 797-808; Carpenter, R.O'B., Journal of The Optical Society of America, Vol. 40, No. 4 (1950), pp. 225-229; Carpenter, R.O'B., Journal of The Acoustical Society of America, Vol. 25, No. 6 (1953).

[3] Harris, S.E.; McMurtry, B.J., and Siegman, A.E., Modulation and Direct Demodulation of Coherent and Incoherent Light at a Microwave Frequency, Applied Physics Letters, Vol. 1, No. 1 (Oct. 1962).

modulation bandwidths have been quite narrow. There is one exception to the above statement, and this will be commented upon later in the report.

The principal difficulty encountered with KDP (and ADP) is in the rapidly increasing power consumption as the modulation frequency is increased. Further, arcing and subsequent breakdown continues to be a problem. Though published dielectric data on KDP and ADP do not indicate the afore mentioned type of trouble (i.e., measurements by Von Hippel[4] and others imply that very low power losses should be encountered, even at microwave frequencies) it nevertheless exists. One possible explanation might lie in the fact that both materials are deliquescent. The presence of slight amounts of water on the surface of these materials could account for the large power losses observed at this laboratory and the low dielectric losses measured by others. The difference lies in the applied electric field strengths. Pure water is known to be an excellent insulator except at field strengths in excess of approximately 300 volts/cm whereupon it suddenly becomes an equally excellent conductor[5]. Therefore, water, even in very small quantities, could appreciably degrade the otherwise good dielectric properties of these two materials. An obvious next step would be to protect the crystals from humidity by means of a suitable coating. However, it was decided instead to first investigate the suitability of two other materials already mentioned. These are: cuprous chloride and quartz. The reason for this decision is contained in the following discussion.

The primary motivation for using KDP and ADP in the first place was because of their large Pockels activity. It was common practice to apply both the electric field and the light beam along the optic Z-axis, thereby realizing the largest induced birefringence for a given applied electric field. A limitation of this mode of operation appears immediately. The overall effect achievable is directly proportional to the applied voltage, and this is a disadvantage when many kilovolts are to be applied at microwave frequencies.

A travelling wave structure similar to that first demonstrated by Kaminow[6] was built, and formed the basis for the X-band modulator previously described. The advantage here is that the overall effect is no longer directly proportional to the applied voltage only, but depends upon the optical path length as well. (This point is discussed more completely in the First Quarterly Progress Report.) This means that applying large voltages to the material is no longer essential since a smaller peak voltage may be made up for by an

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[4]Von Hippel, A. R., <u>Dielectric Materials and Applications</u>, J. Wiley and Sons, New York (1954).

[5]Dorsey, N. E., <u>Properties of Ordinary Water Substances</u>, Reinhold Publication (1940).

[6]Kaminow, L. P., <u>Phy. Rev. Letters</u>, <u>6</u> (1961), p. 528.

increased optical path length. It is, therefore, not necessary to be too greatly concerned with high electro-optic activity. Of equal and perhaps greater concern is the optical and dielectric properties of the material. It might also be pointed out that the travelling wave modulator with KDP utilized a TM mode in its operation. Again, the light path, electric field, and the optic Z-axis of the crystal are collinear. A much wider bandwidth capability is possessed by structures utilizing (TEM) or transverse electric and magnetic modes. These structures require an electro-optic material that operates with the light path and the applied electric field perpendicular to each other. Both cuprous chloride and quartz are such materials.

Cuprous chloride has several desirable properties. In the pure state, it is known to be transparent to electromagnetic radiation of wavelengths between 0.4 micron and approximately 15 microns. It is relatively insoluble in water; only to the extent of 1.52 parts per 100 parts of water. It melts at 422°C and boils at 1366°C; its specific gravity is 3.53. It is a natural mineral (nantokite) occuring as a white crystalline solid with an optical index of refraction of 1.973. It is a cubic crystal of the ditesseral (T_d) group and is known as a transverse electro-optic material. Because of its symmetry, the material is describable in terms of three electro-optic coefficients, all of identical magnitude.

In general, the electro-optic effect is expressed in terms of a change in the inverse dielectric constant along a given crystalline direction. In the case of cuprous chloride, it is necessary to view the situation from a coordinate system having one axis (X-axis) oriented along the (1, 1, 1) direction of the crystalline axes. If a beam of light is directed along the special X-axis, it will experience either one of two indices of refraction depending upon its polarization. The inverse square of these indices is given by:

$$\frac{1}{N^2} = \frac{1}{N_o^2} \pm \frac{1}{\sqrt{6}} \gamma_{41} E_Z \qquad (1)$$

where

N = altered index of refraction

N_o = original index of refraction of the cubic crystal

γ_{41} = electro-optic coefficient

E_Z = applied electric field, transverse to the X-axis

and the (±) signs correspond to the direction of polarization of the light (orthogonal possibilities). Therefore, if we construct a rectangular bar of cuprous chloride, the length of which is oriented parallel to the (1, 1, 1) direction in the crystal, linearly polarized light travelling the length of the bar may be made to undergo alternating birefringence by applying an alternating electric field across the bar (Figure 1).

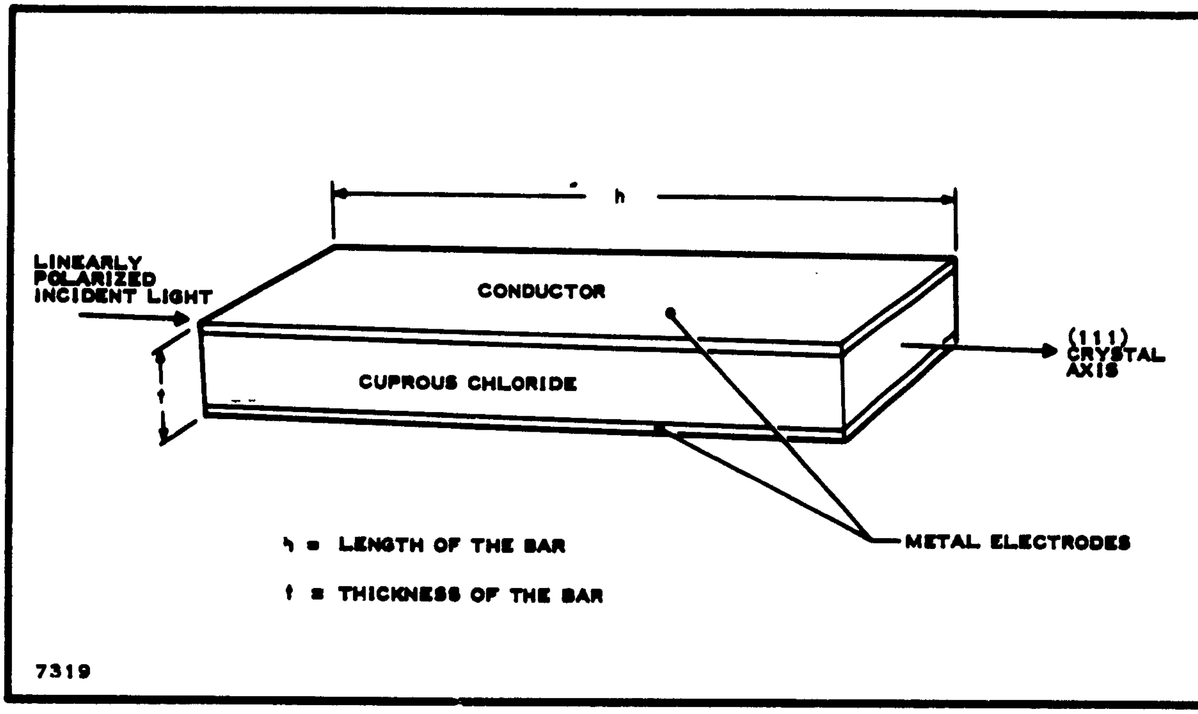

Figure 1. Modulator Geometry for TEM Mode

Voltage of value $V_Z = E_Z t$ is applied across the metal electrodes. The induced difference in phase ($\Delta\phi$, in radians) generated between the two orthogonal polarized light components travelling the length of the bar is given by;

$$\Delta\phi = \frac{2\pi h\, N_o^{\,3}}{\lambda_o \sqrt{6}} \, \gamma_{41} \, \frac{V_Z}{t} \, . \tag{2}$$

Here, λ_o = free space light wavelength. The above formula for ($\Delta\phi$) is valid provided either one of two possible conditions hold; i.e., (1) the travel time for the light beam in the bar is much less than the period of the applied modulation (low frequency case) or (2) though the light beam travel time may be equal to or greater than the period of the applied modulation, the phase velocities of the light and the travelling modulation microwave in the crystal must be matched, and now the induced change in travel time of the light beam through the bar must be much less than the period of the modulation. (See First Quarterly Progress Report for additional discussion of this point.) As an example, let us choose h = 10 centimeters: t = 1 centimeter and λ_o = 1.0 micron. Also, N_o = 1.973, with $\gamma_{41} = 3 \times 10^{-10}$ centimeter/volt. We have $\Delta\phi \approx 6 \times 10^{-4}\, V_Z$, and for an applied voltage of $V_Z = \pm\, 2.5$ kilovolts, we have a corresponding phase shift of $\Delta\phi = \pm\, \pi/2$ radians, enough for 100 percent amplitude modulation.

Quartz may also be used, but with certain special precautions. In any event, a simple configuration of polarizer and analyzer does not yield a convenient amplitude modulation. A travelling wave modulator design presently being developed at this laboratory utilizes quartz in such a way as to give rise to phase modulation only. In this case the light is directed along the electric (Y-axis) of the crystal, and the electric field is applied transverse to the light path, and parallel to the mechanical (X-axis). The incident light is first linearly polarized with its electric vector aligned with the crystalline X-axis. The device configuration is similar to that contemplated for cuprous chloride, shown in Figure 1. Quartz has some properties better suited than the cuprous halides to the present application and some less suited. In particular, its optical transmission properties are better. It has the considerable advantage of being readily available. However, it suffers from the disadvantage of possessing an electro-optic (Pockels) activity lower by slightly more than an order of magnitude than cuprous chloride. Preliminary experiments have been conducted on quartz with the intention of better understanding which alignments are worth trying in a travelling wave structure and which are not. Because of its rotary power (optical activity), quartz cannot be used for modulation with light directed along the optic Z-axis. Since it is therefore necessary to direct the incident light perpendicular to this axis, the natural birefringence of the material gives rise to an optical light bias, when placed between crossed polarizer and analyzer, that is difficult to remove.

It has recently been reported[7] that a frequency modulation-to-amplitude modulation converter, using calcite, was successfully demonstrated. The basic idea is that in any doubly refracting crystal, the difference in phase retardation between the ordinary and extraordinary ray when passing through the material, is wavelength dependent. If the frequency of the incident light has been previously modulated, by a rapid phase modulation for example, the calcite and a linear analyzer can bring about a conversion to amplitude modulation to an extent unattainable with ordinary polarizers and quarter-wave plates. Although the device cannot product 100-percent amplitude modulation for an arbitrarily small phase modulation, the trade-off is nevertheless considerable. The optimum length of the material for maximum conversion to amplitude modulation, is a function of the modulation rate ω_m and may be computed according to the relation:

$$\mathrm{Sin}\left[\frac{\omega_m L_{opt} (N_\omega - N_\epsilon)}{2C}\right] = 1 \qquad (3)$$

or

$$L_{opt} = \frac{c}{2f_m (N_\omega - N_\epsilon)} , \qquad (4)$$

[7] Harris, S.E., Record of Northeast Electronics Research and Engineering Meeting (1962).

where

N_ω = ordinary index of refraction

N_ϵ = extraordinary index of refraction

c = velocity of light in free space.

In this case, if ϕ_m = phase modulation (in radians), then the amplitude modulation index M is given by:

$$M = 2J_1 (\pi\phi_m).$$

M = 1 (100-percent modulation)) when $\phi_m \approx 0.58$ radians.

Now since

$$\phi_m = \frac{\pi h N_o^3 \gamma E_o}{\lambda_o} \qquad (5)$$

where

h = length of the electro-optic material

N_o = unperturbed index of refraction

γ = electro-optic or Pockels coefficient

λ_o = free space light wavelength,

and if we substitute the appropriate values for quartz, i.e.,

$N_o = 1.5$

$\gamma = 0.23 \times 10^{-10}$ cm/volt ("direct" Pockels coefficient)

$\lambda_o = 10^{-4}$ cm,

we find that:

$$\frac{hV_o}{t} \approx 1.4 \times 10^5. \qquad (6)$$

If, for example, we choose h = 10 centimeters, and the thickness (t) of the sample = 1/5 centimeters, we get:

V_o = Applied modulation voltage transverse to the light path

= 2.8 kilovolts.

This is the voltage required to obtain 100-percent amplitude modulation using the above described configuration. This is a remarkable result and, if we are to believe the published electro-optic data on quartz[8], a very encouraging one. Presently the appropriate pieces of quartz are being prepared and the fabrication of an appropriate (TEM) travelling wave driver is underway. Rutile has been chosen as the FM to AM converter material instead of calcite

[8] Cady, W.G., Piezoelectricity, McGraw-Hill, New York (1946).

for two reasons: (1) The difference in value between N_ω and N_ϵ is twice as large as in calcite, and (2) it is considerably easier to fabricate and work with than calcite.

In the meantime, an informal program has been initiated to prepare a few samples of pure cuprous halide single crystals. One of the more difficult parts of the crystal preparation program is in obtaining a good single-crystal seed from which to grow a larger one. The Teal-Little method is being used for growing the crystal. A common impurity found in these crystals is the cupric ion which absorbs light of wavelength around 0.9 micron. This ion is responsible for the blue coloring of most cuprous chloride crystals. This ion must be eliminated, and the zone refining process is being utilized for this purpose. Other precautions which will minimize the cupric impurities include growing the crystal under a reducing environment. It has been generally found that palladium purified hydrogen, in carefully controlled quantities, serves this function very well. We anticipate making preliminary measurements on pure single crystals of cuprous chloride very soon. Plans call for their employment in a modulation configuration where the applied electric field is perpendicular to the light path. The necessary arrangement is the one already described for quartz. This leads strictly to a phase modulation of the light only, and in such a form that direct conversion to amplitude modulation (and hence an effective demodulation by an intensity sensitive receiver) is quite inefficient except for the method discussed. Wideband phase modulators of this type are quite feasible, and as a matter of fact, the successful fabrication of one with a configuration very similar to that presented here for quartz, but using ADP, has been recently reported.[9]

Even though ADP and KDP possess large Pockels activities they nevertheless suffer from instability problems of the type discussed. Quartz, and hopefully cuprous chloride, are considerably more stable and desirable optically. It is materials such as these that will be given considerable attention in the next quarter.

2. Measurements Program

A helium-Neon gas phase optical maser has recently become available in the laboratory. It is capable of delivering very monochromatic, coherent light of wavelength $\lambda = 6328$ Å, and in a highly directed (parallel) beam. It is anticipated that this device, used as the light source, will allow considerably more precise measurements on the optical-electric properties of new materials. For example investigation of ferroelectrics near their Curie point should be greatly facilitated. It will be recalled, from the First Quarterly Progress Report that some of the effort was to be expended toward exploration of Curie-Weiss behavior in the optical range. In particular, it was hoped that ferroelectric materials would exhibit appreciable changes in index of refraction, under the application of an electric field, when near their Curie temperature. Upon fabricating these materials into suitable prisms, a

[9] Peters, C. J., Wideband Coherent Light Modulator, NEREM Record (1962).

determination of their refracting ability with and without electric fields should be a relatively straightforward task using the "laser." Although it is not expected that these materials will respond to microwave frequencies, they should nevertheless show a high change in index of refraction, thereby lending themselves to possible optical scanning applications.

Prisms of both strontium titanate and barium titanate have been constructed. These two materials will be evaluated soon.

Some considerations and experiments, gone into during this last quarter, which could fall into the category of a measurements program, concern "modulation heterodyning." If one considers the resulting light intensity of a light beam having traversed two modulation cells of modulation frequencies ω_1 and ω_2 and modulation indices M_1 and M_2 respectively, one finds that besides the modulation just described, there are two additional terms, of modulation index $M_1M_2/2$, and frequencies $(\omega_1 - \omega_2)$ and $(\omega_1 + \omega_2)$. This result, though not a new one, has nevertheless some interesting consequences for the optical modulation and demodulation program. For example, it was stated at the beginning of this section that it is relatively easy to build narrow band (a few mcps) continuous light modulators in the microwave range, and to build fairly wideband modulators, extending from dc up to 500 mcps or perhaps somewhat higher. It is more difficult to build wideband (even a few 100 mcps) modulators centered at microwave frequencies.

As was later discussed, new modulators involving new electro-optic configurations will (and are) giving rise to wider bandwidths and higher center frequencies. However, there will always be limitations and cost considerations of one kind or another, and the following considerations might well be worth pursuing.

If one is interested in transmitting a very large amount of information over a light beam, this information might, in many cases, be separable into a number of individual wideband channels. If so, the modulation could be accomplished by the wideband modulators originating from dc, and a frequency translation into an appropriate portion of the microwave spectrum could be accomplished by the narrowband modulators following in tandem. Many individual channels could be so placed and therefore more complete advantage could be taken of the inherently wideband nature of the light beam. At the receiver, the individual wideband channels could again be translated down and fed into individual wideband demodulators originating at dc. Though involving more pieces of equipment, this approach could be competitive and/or complementary to the development of single, very wideband microwave modulators and demodulators. Work is in progress toward the demonstration of this procedure for carrying multiple channels on a light beam.

3. Non-Pockels Modulation

In the First Quarterly Progress Report, a preliminary analysis was made as to the effects on a light beam allowed to transverse a travelling microwave structure filled with a material which changed its index or refraction under the application of an electric field. No particular birefringence was assumed, merely a change in index. Calculated expressions for the phase and frequency modulation that resulted gave encouraging results. Low microwave dielectric loss and efficient excitation of the material were primary requirements. Since then, some electro-optic materials, namely quartz and the cuprous halides have appeared the most suitable for this application. These materials and the manner in which they will be used, have already been discussed here. It might be worth pointing out that, except for an initial polarization of the light beam along one of the crystalline axes, and the additional advantage of utilizing transverse electric fields, the results and operation are as described in that report.

Again in the First Quarterly Progress Report, an analysis and some experiments on the phenomenon of frustrated total internal reflection or "photon tunneling" were described. The use of this phenomenon in the amplitude modulation of light was described as well as certain phase and polarization characteristics. Recently, some thought has been given to the possible models one might use for the optical characteristics of a semiconductor PN junction near its band edge. "Photon tunneling" would appear to play at least a partial role. Some optical experiments are presently being carried out using degenerately doped PN wafers of gallium arsenide. They are intended to determine whether or not the depletion layer formed at the junction exhibits any varying optical properties when variable bias is applied to the junction.

In addition, gallium arsenide light emitting diodes (of the type described in the First Quarterly Progress Report) have been utilized to obtain excellent audio signals over a distance of approximately 1000 feet using conventional batteries and circuits in hand-held units. The optical demodulator is a silicon photovoltaic cell.

Gallium arsenide has recently been reported to exhibit "lasing" action.[10] This has been achieved by a number of organizations including Texas Instruments.

The fact that semiconducting solids can be made to perform as "lasers" is a great step forward in the area of optical data processing. Simple modulation capability and the flexibility of materials are ideal characteristics possessed by semiconductors in the laser application.

Further experimentation, development, and testing of such devices is presently being pursued.

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[10] Nathan, M.I., Dumke, W.P., Burns, G., et al, "Simulated Emission of Radiation from GaAs PN Junctions," Applied Physics Letters, Vol. 1, No. 3 (Nov. 1962).

B. DEMODULATION

1. Photodiodes

In the First Quarterly Progress Report, a number of photodiodes were described and their pertinent parameters listed. In addition, an analysis of the diode equivalent circuit was begun, together with some tentative remarks concerning the microwave receiver. Some conclusions that could have been made were not made. They will be made in this report.

In considering the available output power from a practical detector, there is a half-power cutoff frequency which occurs below the microwave range, which is useful in describing the performance of the diode. Because of this cutoff frequency, photovoltaic detectors might be limited to low microwave frequencies in most applications (around 1 or 2 Gcps). Although the quantum efficiency is high, the device efficiency is quite low.

Proceeding from the formulas presented in the First Quarterly Progress Report, we can write the expressions for the available output power (P_{av}) into the load from a conjugately matched photovoltaic detector, and the aforementioned cutoff frequency (f_c). The circuit assumed is given in Figure 2.

We assume only that $R_d >> R_b$. We have:

$$P_{av} = \frac{i_g^2}{4 G_d [1 + \omega^2 C_o^2 (R_b R_d)]} \tag{7}$$

and

$$f_c = \frac{1}{2\pi C_o (R_b R_d)^{1/2}} \; . \tag{8}$$

As can be seen from the equations, P_{av} begins at a value of $i_g^2/4G_d$ for $f = 0$ and falls to one half of this value when $f = f_c$. Beyond this

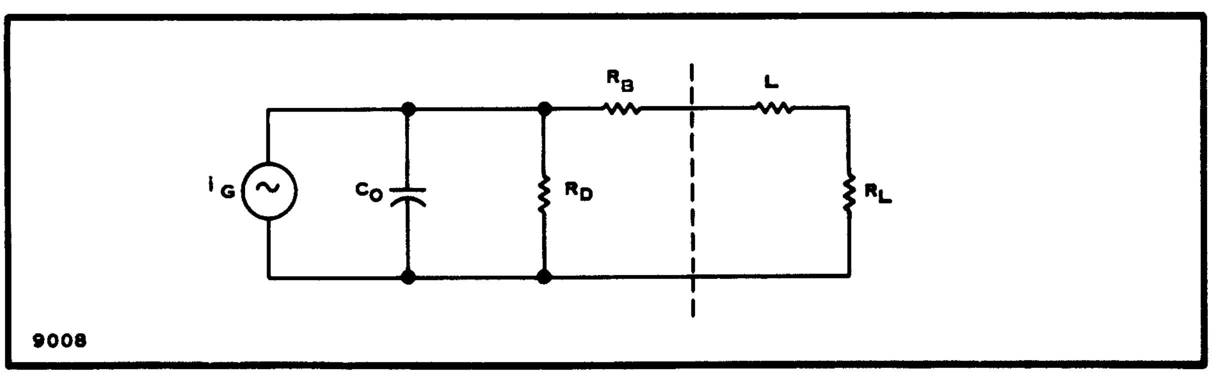

Figure 2. Equivalent Circuit for Diode and Matched Load

point, P_{av} falls at the rate of 20 db per decade. A more important parameter is the NEP (noise equivalent power). We recall that it is defined as the incident power required to achieve unity signal-to-noise ratio at the load. At microwave frequencies we need consider only shot noise. Here, all the resistances can be replaced by their equivalent noise generator and resistor. All the generators may be merely summed due to their statistical independence. The noise output power (N) is simply:

$$N = \sqrt{i^2_{NT} R_L} = 2kT\Delta f \tag{9}$$

where

k = Boltzmann's constant

T = temperature in °K

Δf = bandwidth.

$\sqrt{i^2_{NT}}$ = effective noise current flowing in the load.

To obtain the NEP, we determine the signal current necessary to give an output of (N). The signal current is expressed as:

$$i_g = nq\eta \tag{10}$$

where

n = number of incident photons per second

q = charge on the electron

η = quantum efficiency.

Remembering that the total incident energy per second is $nh\nu$, where h = Planck's constant, and ν = frequency of the incident light, we can determine the NEP as:

$$NEP = \frac{h\nu}{q\eta} \left[8kT\,\Delta f\,(1 + \omega^2 C_o^{\,2} R_b R_d)\right]^{1/2} . \tag{11}$$

Typical numerical values of some of the quantities just defined may now be listed.

For most of the diodes fabricated so far, we might expect that on the average:

$$C_o = 5 \text{ pf};\ \ R_b = 5\Omega;\ \ G_d = 10^{-6} \text{ mhos}. \tag{12}$$

In this case,

$$f_c = 143 \text{ mcps}$$

which is below microwave frequencies even though the parameter values listed are quite good. A multiplication of C_o and R_b leads to an RC "time constant" equivalent to a half power frequency of approximately 7 Gcps. If an extremely large amount of incident light intensity is readily available (as for example, in a pulsed ruby laser) it would be this latter half power cut-off frequency that is important. However, in most applications incident light intensity is low, and power transferred to a load is very important. Here f_c is the pertinent parameter.

To best obtain an estimate of the relative performance of photovoltaic detectors and photomultiplier tubes (for example) we derive, from the equation for the NEP, the number of photons necessary to achieve unity signal-to-noise ratio. For 1μ radiation, $\eta = 1$, and using the circuit values previously given, we have:

$$n = 1.14 \times 10^6 \left[\Delta f \left(1 + \frac{f^2}{f_c^2}\right) \right]^{1/2} . \tag{13}$$

This can be a substantial number of photons even when operation at microwave frequencies with wide bandwidths is <u>not</u> being considered. For a 10^4 cps bandwidth, at 1.4 Gcps center frequency, the number of photons is $n = 1.14 \times 10^9$. In terms of NEP this is 2.27×10^{-10} watts. Note, this is not radiant intensity in watts/cm^2 but the actual power striking the junction of perhaps only 0.01 cm^2. Now, a photomultiplier tube at 1μ has a quantum efficiency of only 1 percent. However, this is also the device efficiency for all practical purposes. In this case, only 100 photons are required in order for the signal to be above the noise of the system. Thus, a photomultiplier tube would appear to be 10^4 better than a photovoltaic detector, assuming equal bandwidths.

What is the maximum performance to be expected from a photovoltaic detector at low light levels, and how is this to be achieved?

One must have, first of all, a minimum limit set on the light gathering ability of the diode. This in turn sets a limit on the size of the junction. Assuming an optical system to be used with normal light sources, a minimum junction diameter of approximately 0.005 cm would still be large enough to permit the focusing and collection of most of the incident light. Second, note that a small G_d is necessary. Above the cutoff, the response is independent of G_d, but since concern is with overall response, it is necessary to consider it. Generally speaking it could be made to approach 10^{-7} mhos. This will be taken as a typical limit.

The next parameter, the series resistance, can be made quite low. In fact, for indium arsenide it could go as low as 0.02 Ω. Here, however, it is not possible to reverse bias the diode without introducing excessive noise. The result is that the capacitance cannot be made very low along with this series resistance. A minimum value of R_b for silicon and germanium diodes would be about 2Ω. Note that since the capacitance enters as the square and R_b only as the first power, the capacitance would be favored whenever a trade-off between the two is possible.

The most important parameter and the one over which one has the most control is the capacitance. While the area cannot be made indefinitely small, the thickness of the intrinsic layer can be made very large. For low capacitance one would choose as small an area as possible, as thick an intrinsic layer as possible, and then reverse bias the diode nearly to breakdown. Accordingly, junction capacitances on the order of 0.04 pf should be possible.

With the values listed above, the cutoff frequency (f_c) of the device would be 0.87 Gcps, just on the lower edge of the microwave frequency range. This is fairly good, since at 8.7 Gcps, the NEP would have increased only 10 db. A typical microwave package is shown in Figure 3.

At microwave frequencies a wide instantaneous bandwidth system is almost precluded unless the signal received is larger than the NEP. In itself the diode is inherently wideband, however. At these frequencies the load R_L is merely equal to R_b and the output power is falling off at the rate of 6 db per octave. Thus, the bandwidth, at least between plus and minus 3 db points from center frequency, is one octave.

2. Measurements

The measurements of the diodes are made by two methods depending on the frequency range. The first method used at frequencies up to 10 mc is shown schematically in Figure 4. The second method used at frequencies above 10 mc is shown schematically in Figure 5. These two methods will now be considered in order.

The method used at frequencies up to 10 mc and shown in Figure 4 employs a nonresonant diode in series with a fairly high impedance load i.e., 10k to 10megΩ. A gallium arsenide light source driven by an audio-to-h.f. oscillator, such as the Hewlett-Packard 650A, is used to provide the modulated source of light. The output of the photovoltaic light detector is then fed into a vacuum tube millivoltmeter as the Hewlett-Packard 400H. The output of the millivoltmeter is then fed into an oscilloscope. The instruments of the physical setup for this measurement appear in the photograph of Figure 6.

At this point, it is necessary to digress long enough to consider the frequency response of the gallium arsenide light source. Its equivalent circuit is shown in Figure 7. An analysis was carried out to determine the frequency response of this device. It was found that resonating the device gave no noticeable improvement in its output since the resistance values are so low. The available power out was found to be:

$$P_o = \frac{v_g^2 R_d}{4R_b^2 (1 + \omega^2 C_o^2 R_d^2)} \qquad (14)$$

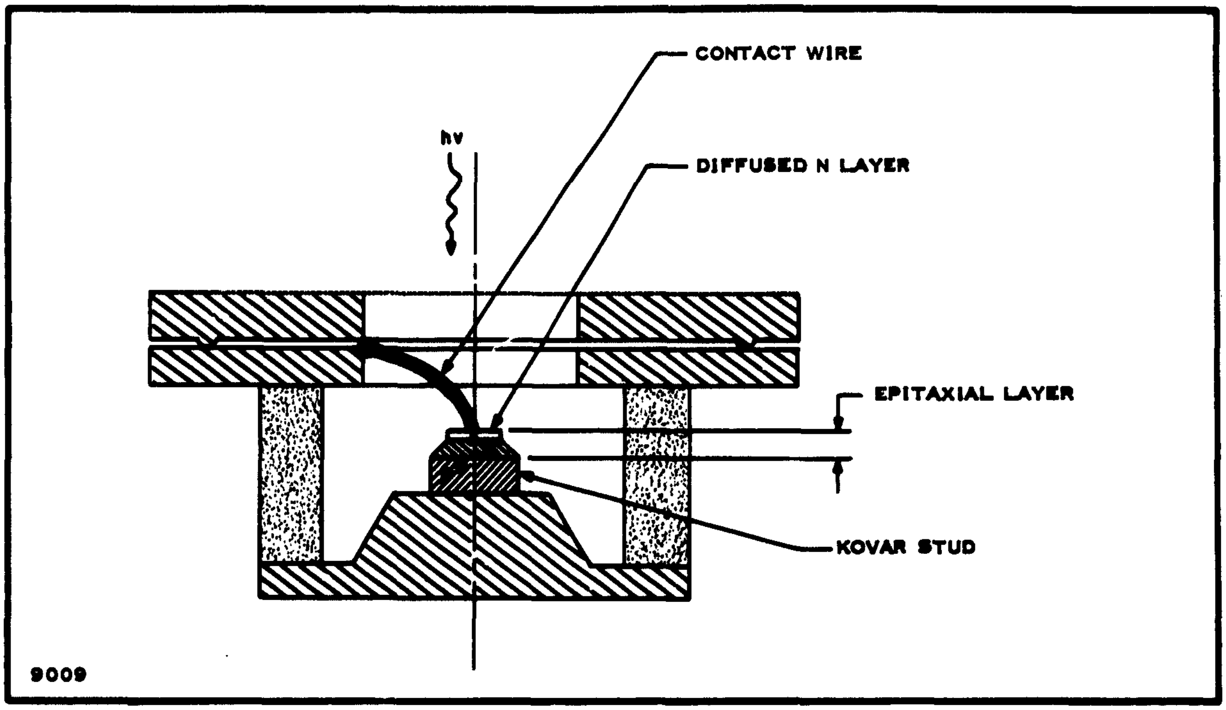

Figure 3. Cross-Section of Microwave Package

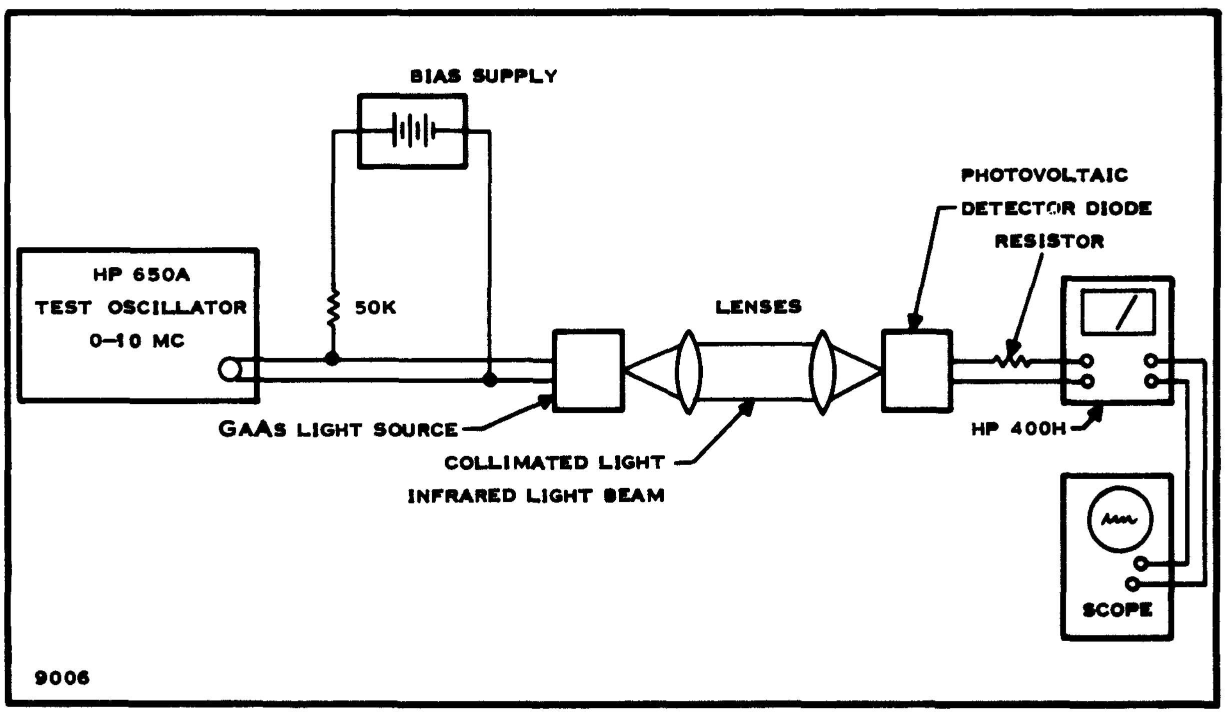

Figure 4. Block Diagram of Measurement Apparatus
(up to 10 mc)

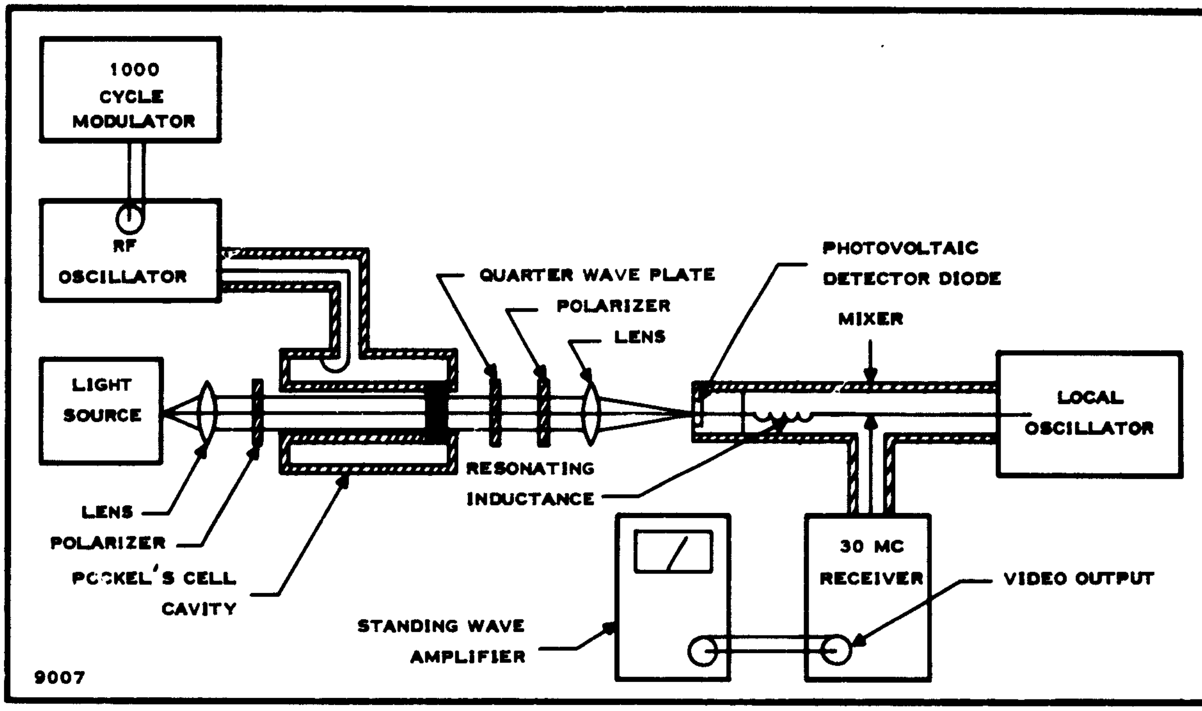

Figure 5. Block Diagram of Measurement Apparatus
(above 10 mc)

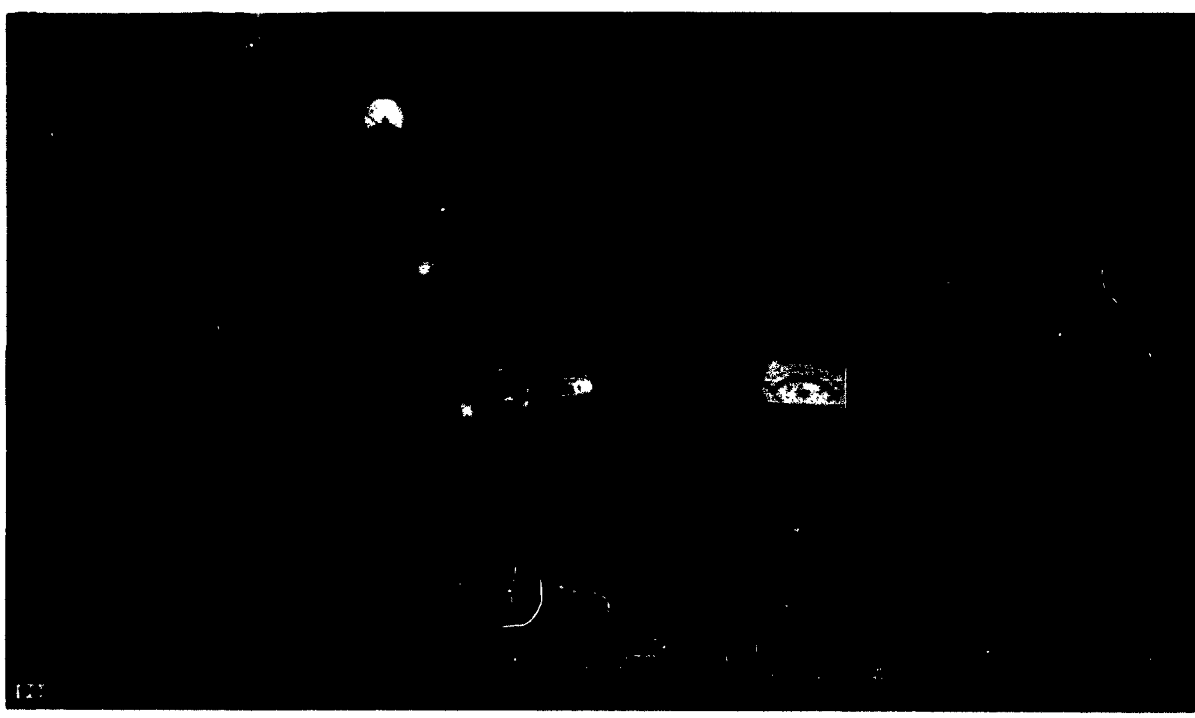

Figure 6. Physical Layout of Measurement Apparatus
(up to 10 mc)

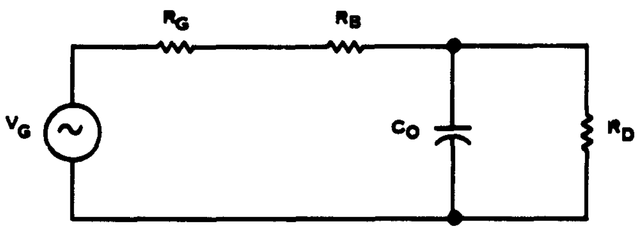

Figure 7. Equivalent Circuit of GaAs Light-Emitting Diode

Typical circuit values at 59 ma current through the diode are:

$$C_o = 10,000 \text{ pf (bias about +1.2 volts)}$$

$$R_d = R_b = 4\Omega.$$

This indicates a cutoff frequency (f_c) of 40 mc for the device. Of course much lower capacitance devices can be made (which also put out less total light) so that the cutoff frequency of this device could be somewhere in the microwave frequency range. However, with the gallium arsenide light source available to us at the present, its use as a constant output modulated source of light is restricted to frequencies below 40 mc. Above 40 mc a Pockel's type modulator becomes the best type of modulator for measuring purposes.

The method used at frequencies above 10 mc and shown in Figure 5 employs a diode with an inductance in series to resonate it. Its output is fed into a 50Ω mixer and then into a 30 mc receiver. The receiver has a video output so that if the modulated source of light has a lower frequency modulation on it such as 1000 cycle modulation, the 1000 cycle output can be received from the video output and fed into a 1000 cycle VSWR amplifier with a 4 to 40 cycle bandwidth. In this way an effective bandwidth of 4 cycles can be achieved if desired. The physical setup for this type of demodulation is shown in the photograph of Figure 8.

The modulation scheme above 10 mc, shown schematically in Figure 5, uses either the gallium arsenide light source or a Pockel's effect modulator driven by a 1000 cycle modulated rf signal.

Some of the modulators that have been constructed for evaluating the Pockel's effect and measuring the diodes are shown in the photograph of Figure 9.

Thus far germanium diodes have been tested to nearly 100 mc and silicon diodes have been tested to nearly 40 mc. The gallium arsenide light source modulator has been used almost exclusively since the diodes tested thus far have had cutoff frequencies (f_c) below 50 mc.

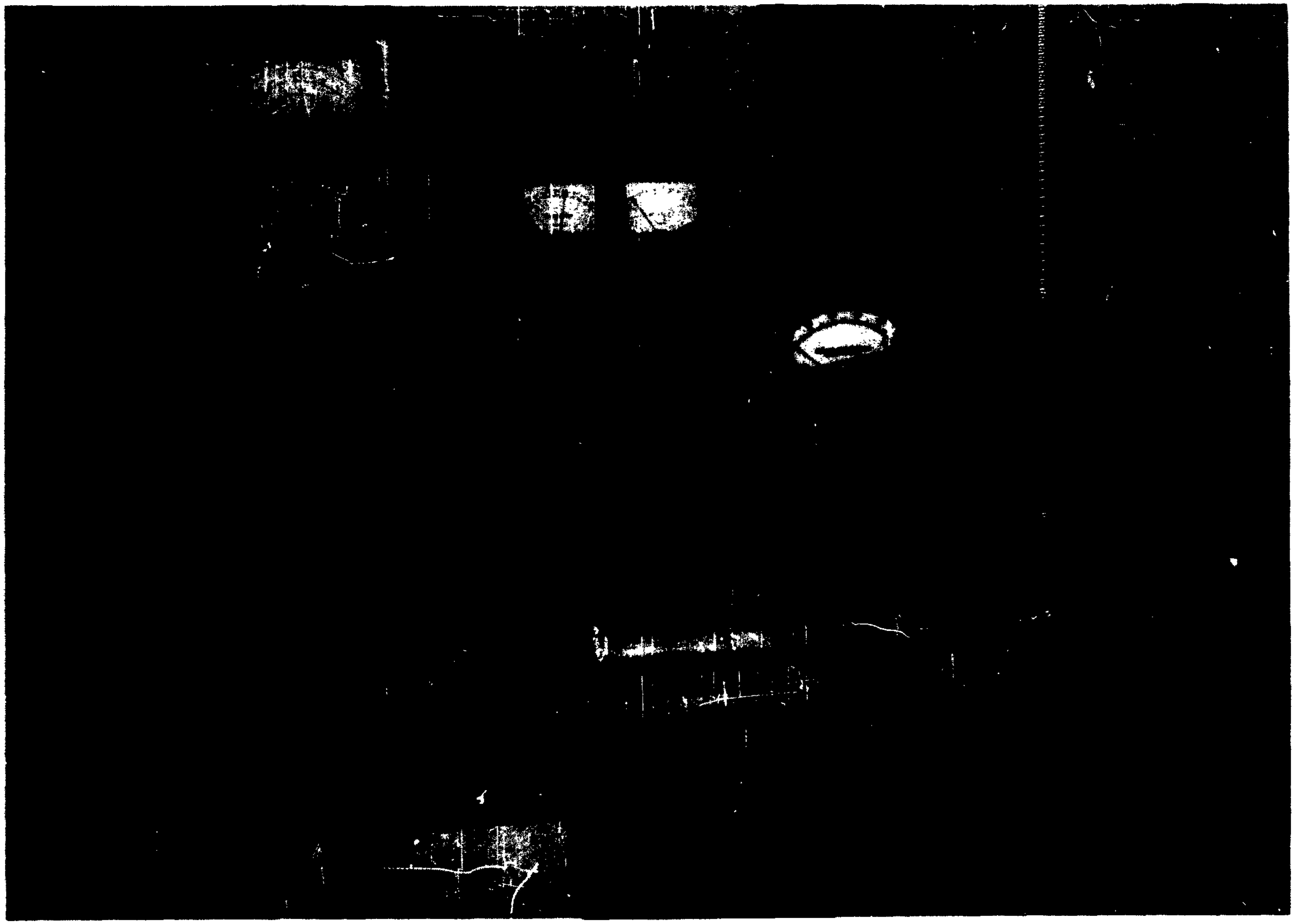

Figure 8. Physical Layout of Measurement Apparatus
(above 10 mc)

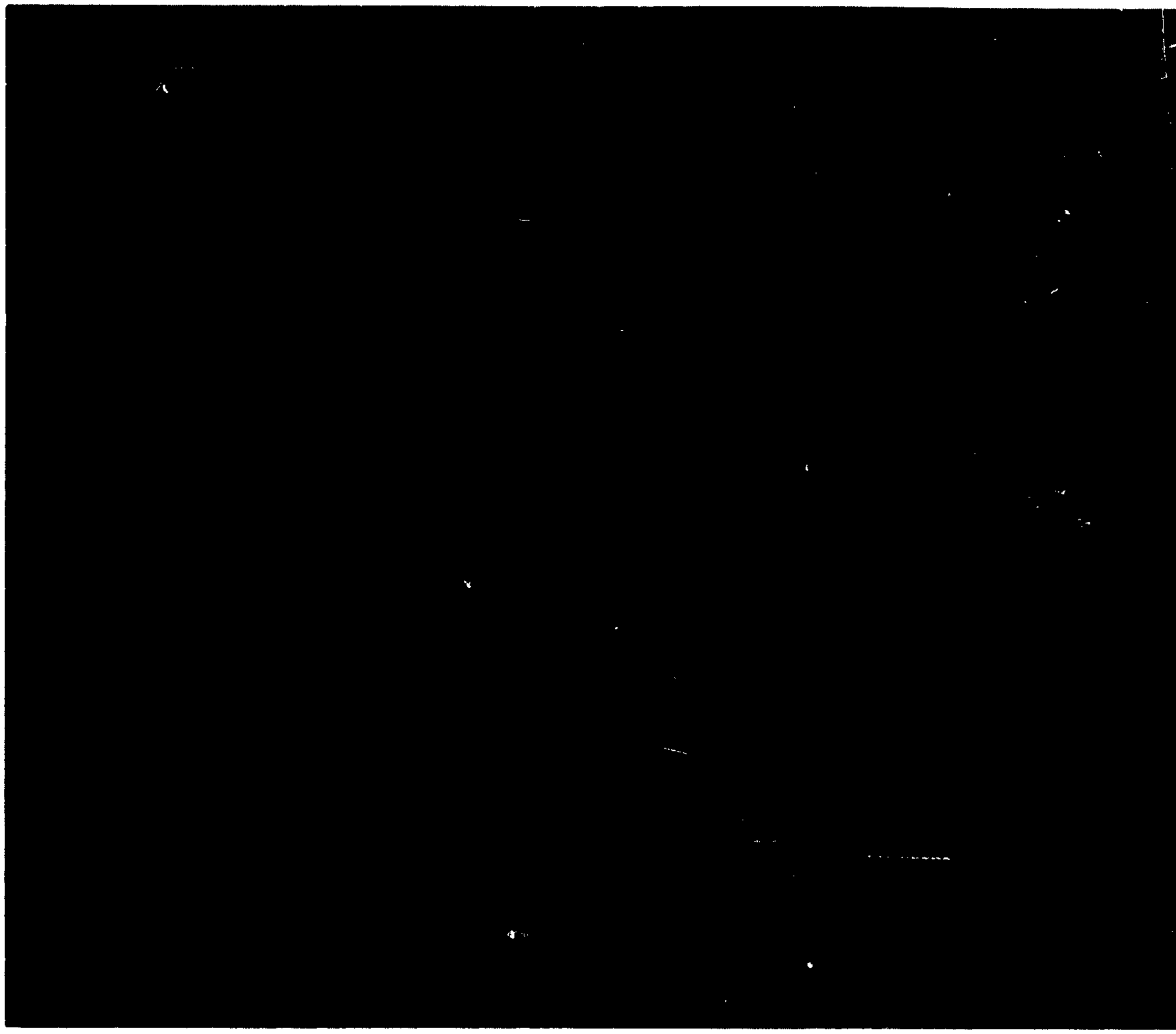

Figure 9. Typical Light Modulators Utilizing Electro-Optic Materials

The highest modulation rate achieved at Texas Instruments with the gallium arsenide light source and a silicon photovoltaic detector has been 900 mcps. In this case, light was passed from the source to the detector via a quartz glass rod. Receiver bandwidth was 5 cps and optimum alignment of all electronic parts (for the anticipated modulation) was required.

Further emphasis, however, will be placed on achieving wideband response in receiving systems using solid-state detectors.

SECTION V

CONCLUSIONS

It has become increasingly apparent that the combining of TEM travelling wave microwave structures and electro-optic materials exhibiting the transverse Pockels effect is highly advantageous. The resulting optical phase modulator is capable of efficient wideband performance. In addition, the recognition of the highly desirable FM to AM conversion properties of doubly refracting crystals (such as calcite) by S. E. Harris is very important. In fact, it makes it possible to use the various travelling wave configurations considered as potential amplitude modulators without resorting to more complicated interferometric conversion techniques. Electro-optic materials with the necessary microwave and optical properties appear to be available. Cuprous halides and quartz are attractive possibilities. The successful attempt to drive gallium arsenide light emitting diodes into "lasing" modes may open up a completely new technology, with applications to radar, displays, and communications systems beyond anything presently visualized.

A deeper understanding of the limitations and advantages of the solid-state photodiode when used as a light demodulator in a matched receiving circuit has been gained. Because of this, more rapid progress is being made in their development and in performing meaningful tests and evaluation.

SECTION VI

PLANS FOR NEXT QUARTER

Next quarter, we will continue development of techniques for phase modulation, frequency modulation, and amplitude modulation of optical radiation using the electro-optic effect. There will be particular emphasis on travelling wave structures.

Efforts will be continued to reduce the dc junction capacitance and series resistance of photovoltaic diodes while keeping their light sensitivity at a maximum. Additional experimental work and development of a test facility for these photodiodes will be continued.

SECTION VII

TECHNICAL PERSONNEL

The following technical staff members were engaged in the work described in the preceding sections. Their resumes of education and experience were included in the First Quarterly Progress Report.

D. D. Eden

K. M. Johnson

G. H. Thiess

G. R. Pruett

R. E. Malm

H. D. Adams

D. E. Michael

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Contract DA 36-039-SC-89221.
Unclassified Report

Description of Work Performed During the Report Period Includes:
A number of wide-band modulators (dc to 500 mc and higher) have been constructed using KDP. Y-cut quartz is being designed into a TEM travelling wave structure.
An optical FM to AM converter using rutile is being prepared.
Good audio reception has been obtained at 1000 feet using gallium arsenide light-emitting

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diodes and silicon detectors in hand-held units.
A number of pill package photovoltaic detectors have been fabricated; typical junction capacitances are on the order of 1 picofarad and typical base resistances are approximately equal to 2 or 3 ohms. A smaller junction diameter of 4 mils appears possible by using new masking and etching techniques.
Modulated light from a gallium arsenide diode has been detected (using an air path) by a germanium photodiode at approximately 100 mcps.
Modulated light from a gallium arsenide diode at 900 mcps was detected by a silicon photovoltaic detector, using, for a light path, a tapered glass rod bonded to both source and receiver.

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